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A SYNOPSIS OF FIELD TEST RESULTS FROM THE GRAVITY GRADIOMETER SURVEY SYSTEM

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The Gravity Gradiometer Survey System (GGSS) has successfully collected data in both airborne and surface vehicle tests. The GGSS navigation system has demonstrated high accuracy and reliability for both the GPS-aiding and fifth-wheel aiding mechanizations. Track-to-track rms repeatability of the gravity disturbance estimates from the surface tests ranged from 2 to 3 mgal for tiepoints about 50 km apart. Comparison of airborne results with truth data yields rms discrepancies less than 5 mgal based on single-track analysis and tiepoint spacing of about 90 km, and less than 2 mgal for multi-track analysis and tiepoints about 80 km apart. Based on these test results, the GGSS offers a significant capability to perform full gravity vector surveys in a timely and economical manner. The authors acknowledge the significant contributions made by J.D. Goldstein, R.F. Shipp, and J.V. White to this test data analysis effort.

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1. INTRODUCTION

The rotating-accelerometer Gravity Gradiometer Survey System (GGSS) was developed by Bell Aerospace and has successfully collected gravity gradients during separate test exercises using an aircraft and an automotive vehicle (a van). The data were collected at a test range located near the towns of Clinton and Sherman in western Oklahoma. Airborne testing occurred between 3 April and 26 May 1987; surface vehicle testing took place during early June of 1987. The Oklahoma site (see Fig. 1-1) was selected because it possesses relatively smooth topography and modest gravity field signature [rms values of 31 milligal (mgal) and 22 eötvös (E)]. In addition, the area contained aircraft support facilities, and adequate (just barely) coverage with the then-current Global Positioning System (GPS) constellation.

Upon completion of GGSS testing, the raw gravity gradients were demodulated, filtered, and compensated for self-gradient and acceleration effects by Bell Aerospace. Outputs

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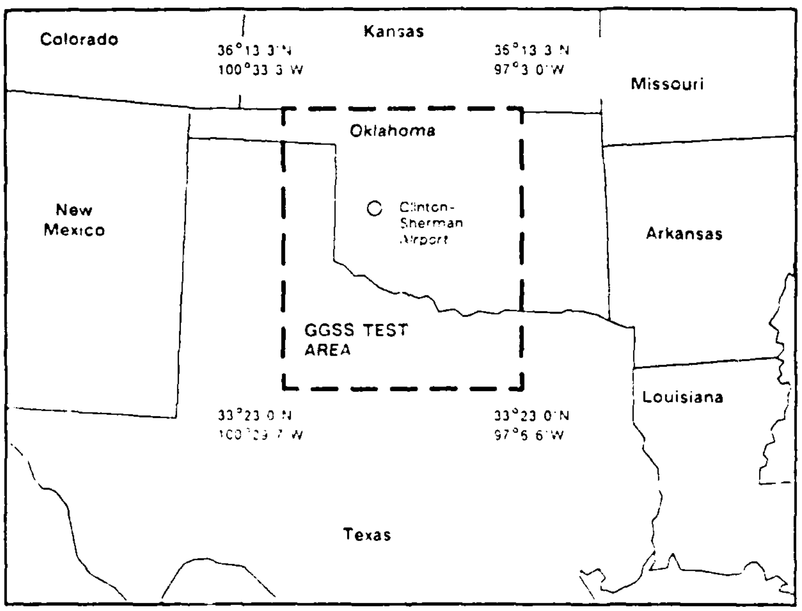


Figure 1-1 Location of GGSS Test Area

of this Stage I processing were transmitted to TASC where the measured gradient data were further analyzed, compensated, and used to estimate vertical gravity disturbances and, for the surface data, all three components of the disturbance vector (Stage II processing). Analysis results were presented to DMA, BMO, and AFGL personnel on 12 August 1987 (Ref. 1), 10 February 1988 (Ref. 2), and on 28 and 29 June 1988 (Ref. 3).

This report summarizes the key results of TASC's analysis. In general, prescreening was required to realize the full potential of the GGSS test data. For the airborne measurements, multi-track analysis of screened tracks demonstrated point gravity disturbance estimation accuracy at the 2 mgal level for a tiepoint spacing of about 80 km; for the surface data, repeatability analysis yielded 2 to 3 mgal rms difference per gravity disturbance vector component when the tiepoint spacing was about 50 km. All issues considered, the GGSS Test Program must be viewed as very successful: the system demonstrated that it could collect data in both the airborne and surface survey modes -- data which could be reduced to yield surface values of the gravity disturbance vector as accurate as available truth data in the area. Furthermore, differences between gradiometer-based estimates of surface gravity and ground truth can be mostly accounted for by known error mechanisms (see Ref. 4).

2. AIRBORNE TEST DATA RESULTS

Airborne GGSS testing involved collecting data in both the north-south and east-west directions along tracks spaced 5 km apart over a 315-km by 315-km area. A total of 56 distinct tracks were preprocessed by Bell Aerospace for further analysis. The data quantities of interest available for each track were: time, GPS and GPS-aided inertial latitude and longitude, platform acceleration in all three axes, speed, heading, and the inline and cross gradients of each gravity gradiometer of the triad. Upon close examination of these quantities, the need to edit the tracks for instances of erratic flight trajectory, loss of signal, and excessive noise was apparent and resulted in the elimination from further processing of 21 tracks. Figure 2-1 shows the location of the "straight" segments of the original 51 tracks (five of the original 56 tracks were located outside the test area) and the resulting "edited" 35 tracks. In addition, the gravity gradients were observed to contain sporadic, mostly isolated spikes, believed to have been due to GGSS computer timing problems. Figure 2-2 presents a sample segment of gradient data, before and after the spikes were removed*.

Based on their length and orientation with respect to the other edited tracks, 20 tracks were selected for estimating gravity disturbances. The gradient data along these tracks were resolved into an appropriate local-level reference frame. Five-minute by five-minute gravity disturbances along each track were then estimated using a Kalman smoothing algorithm. The smoother included error models for the GGSS white noise floor [as identified from Power Spectral Densities (PSDs)], the gradient bias uncertainty (based on track length and PSD), and the uncertainty associated with each tiepoint (rms uncorrelated error of 2.0 mgal). Single-track spectral analysis indicated gradient noise power ranging from 350 to 1700 E^2/Hz (double-sided PSD). Results for individual tracks are presented in Table 2-1. Gravity disturbance estimates were compared with corresponding quantities derived from an available five-minute by five-minute mean gravity disturbance truth dataset. The truth values were interpolated along each GGSS track using a four-point bilinear smoother. Along the best tracks, the vertical component of the gravity disturbance vector could be recovered with an rms error of about 5 mgal for tiepoints over 200 km apart. The rms accuracy improved to 2 to 4 mgal when the tiepoint spacing was reduced to about 90 km.

* Removal was effected by matched filtering and subtraction of detected spike waveforms based on the impulse response of Bell's demodulator filter.

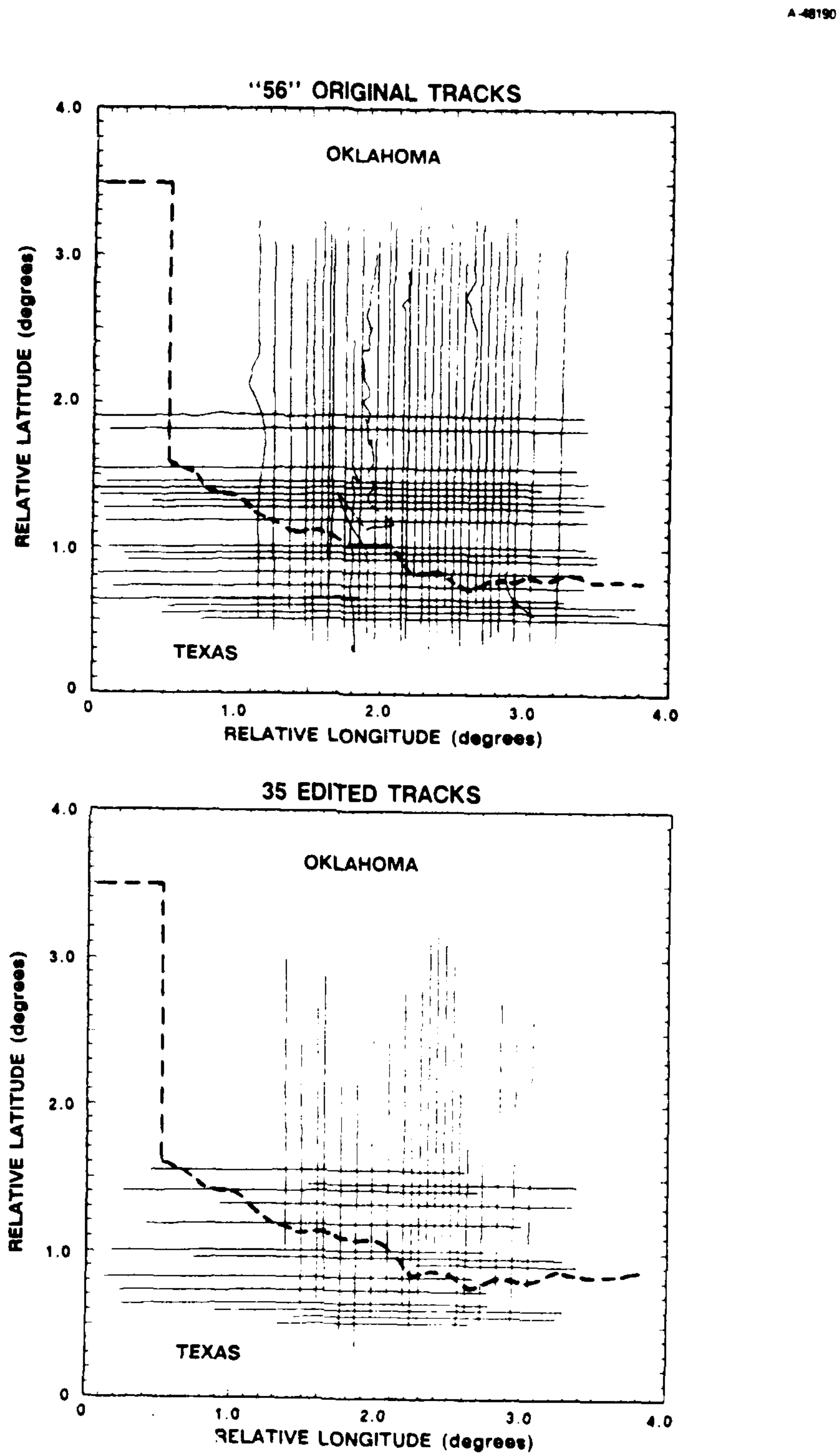


Figure 2-1 Effect of Editing on Original Airborne Data Tracks

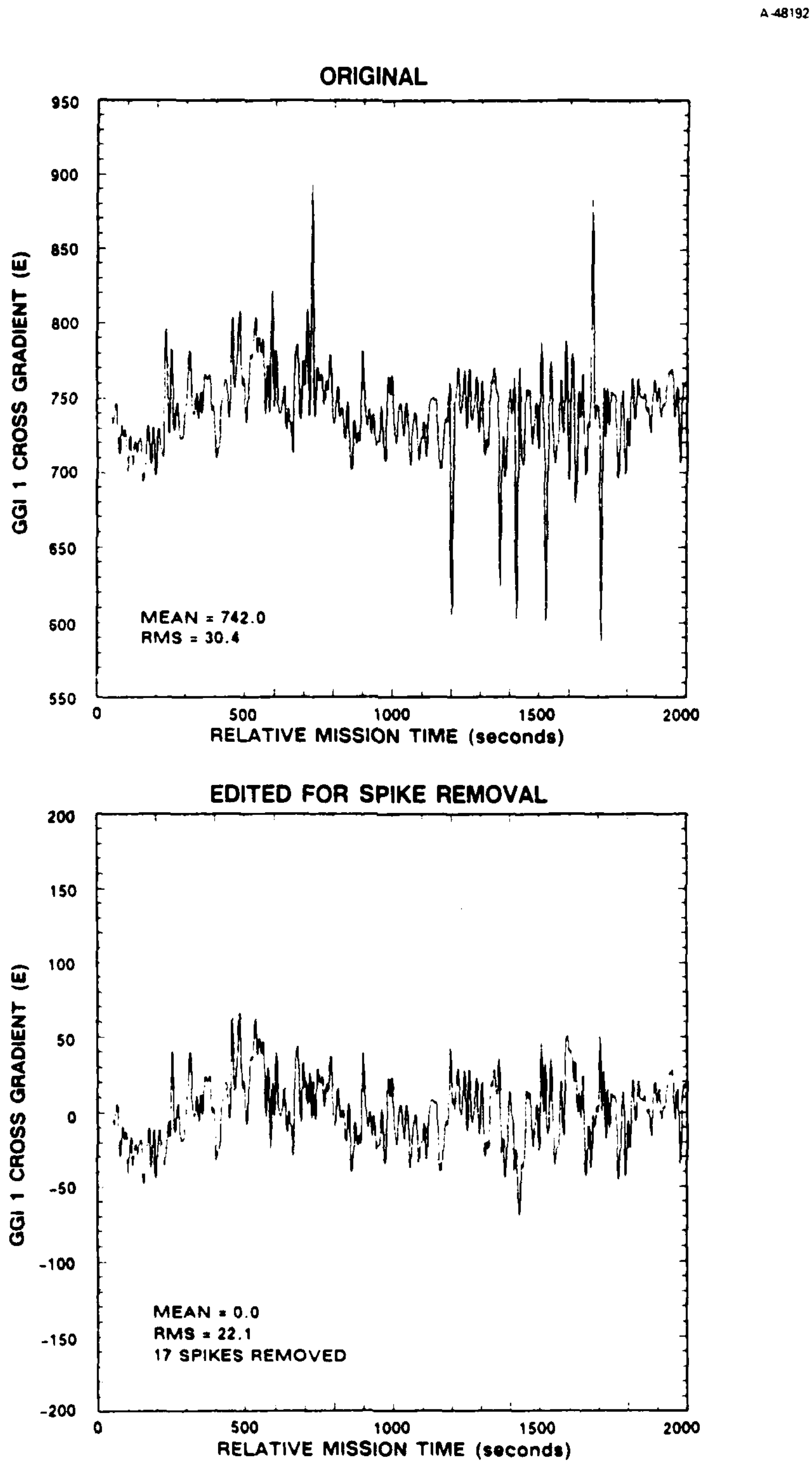


Figure 2-2 Example of Spike Removal (Track 35 South)

Table 2-1 Single-Track Analysis Results

BELL TRACK NUMBER/DIRECTION	WHITE NOISE LEVEL (E^2/Hz)	RMS ERROR (E)
30 S	1700	14.6
31 N	400	7.1
33 S	800	10.0
35 S	600	8.7
39 S	400	7.1
41 N	1000	11.2
42 S	900	10.6
43 S	900	10.6
47 S	1600	14.1
48 N	800	10.0
10 W	1000	11.2
12 W	400	7.1
18 W	700	9.4
19 E	1700	14.6
20 E	350	6.6
22 (I) W	700	9.4
24 (I) E	700	9.4
24 E	1000	11.2
25 W	1700	14.6
27 E	650	9.0
Mean	900	10.3

Notes:
1) The (I) designation refers to a track from an early, first-look dataset provided by Bell (11 tracks). In each case, the quality of the early data was better than the later, reprocessed version of the same track.
2) The rms values are based on one sample every eight seconds for a resolution of 0.88 km.

A multi-track analysis with the TASC template algorithm (Refs. 5 - 9) was then performed using the data within the area bounded by the intersection of 13 of the tracks processed individually (see Fig. 2-3). Selection of the 13 tracks was based on the need to have adjacent (or nearly adjacent) segments of "good" data over as large an extent as possible. The template algorithm was optimized for the Clinton-Sherman Attenuated White Noise

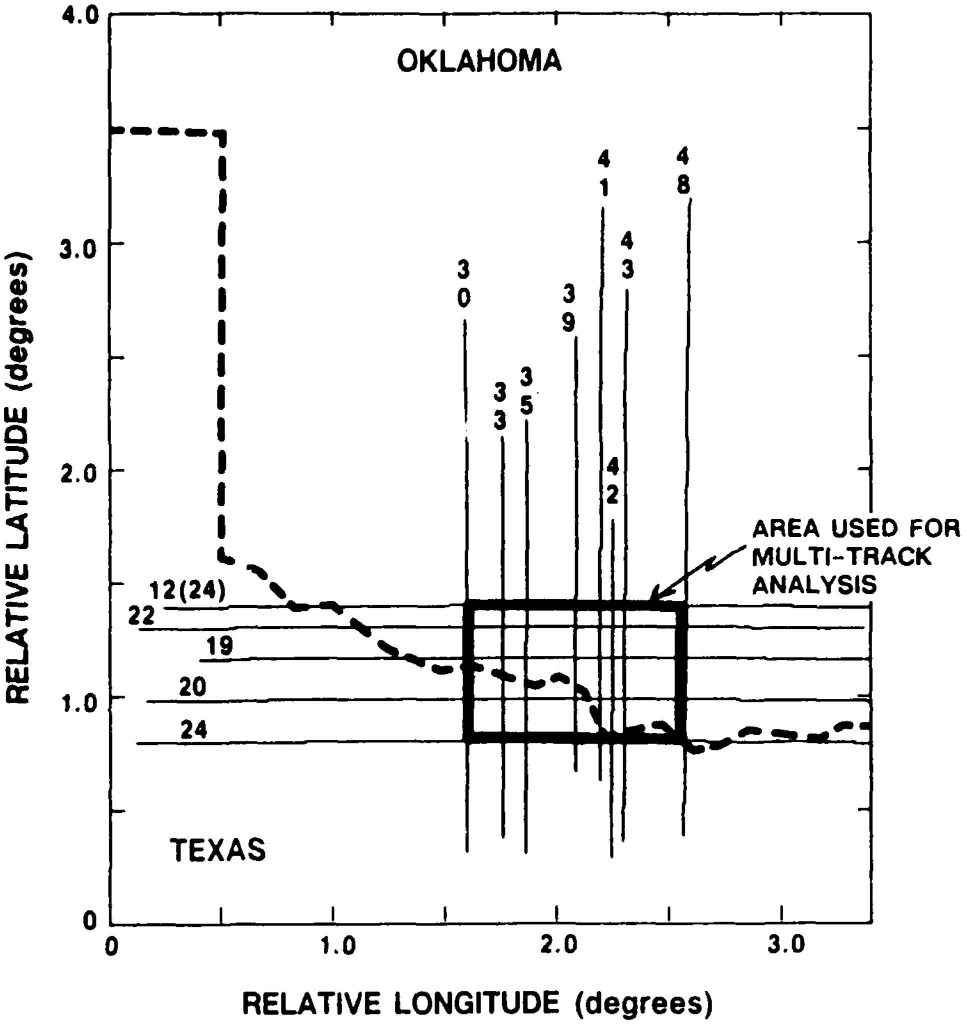
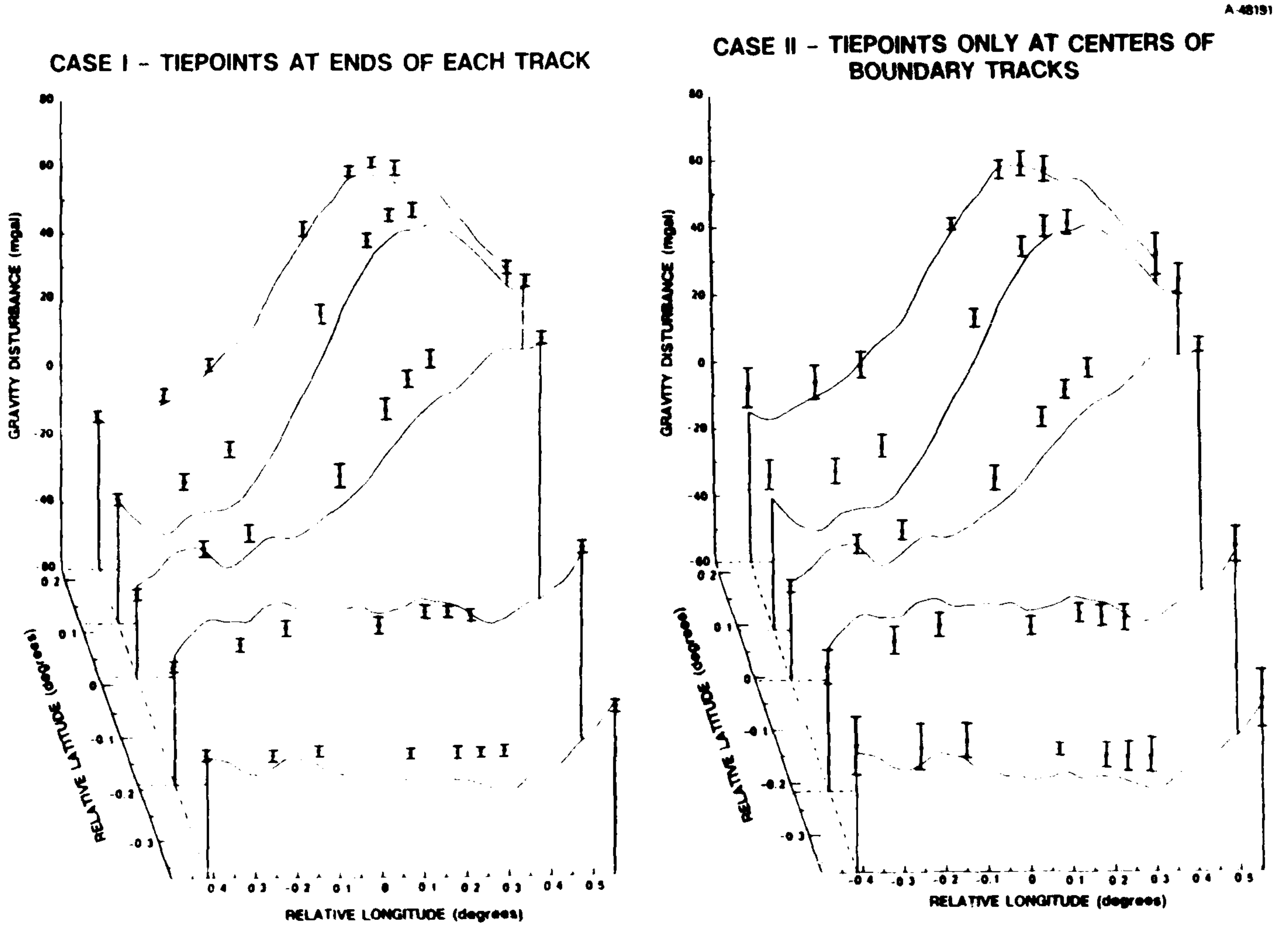


Figure 2-3 Track and Area Selection for Multi-Track Analysis

Statistical Gravity Model (Ref. 10), data-derived error models for the GGSS measurements, and the rms uncertainty of the tiepoint values. Results of estimating the vertical component of the disturbance vector at all track crossings in the overlapping area (40 points) are presented in Fig. 2-4. A comparison of these multi-track estimates with corresponding surface truth values is presented in Table 2-2. The two distinct cases considered were 1) tiepoints at the ends



NOTES:

1 - SOLID CURVES ARE SINGLE-TRACK ESTIMATES

2 - ONLY EAST-WEST TRACKS ARE SHOWN

3 - I SYMBOL DENOTES MULTI-TRACK ESTIMATES AND PREDICTED rms ERRORS

Figure 2-4 Multi-Track Analysis Results

Table 2-2 Summary of Multi-Track Comparisons

CASE	RMS ERROR: ALL POINTS (mgal)		RMS ERROR: NON-TIEPOINTS (mgal)		WORST CASE ACTUAL ERROR (mgal)
	PREDICTED	ACTUAL	PREDICTED	ACTUAL	
Tiepoints at Ends of Each Track	1.93	1.64	2.33	2.16	3.72
Tiepoints at Centers of Boundary Tracks	4.34	3.27	4.53	3.44	8.77

each track, and 2) tiepoints only at the centers of the boundary tracks. For each case, the actual rms error agreed well with the predicted rms errors provided by the template algorithm covariance calculations.

3. SURFACE TEST DATA RESULTS

Surface GGSS testing was performed along a 53-km stretch of paved road near the Clinton-Sherman airfield. Two tracks of Stage I processed repeat data (one on 6 June 1987, the other on 9 June) were provided by Bell Aerospace. These tracks commenced at gravity survey station number 7, crossed station number 6, and ended near station number 9 (see Fig. 3-1). The data quantities of interest available for each track were: time, fifth-wheel aided inertial latitude and longitude, altitude, heading, and the inline and cross gradients for each

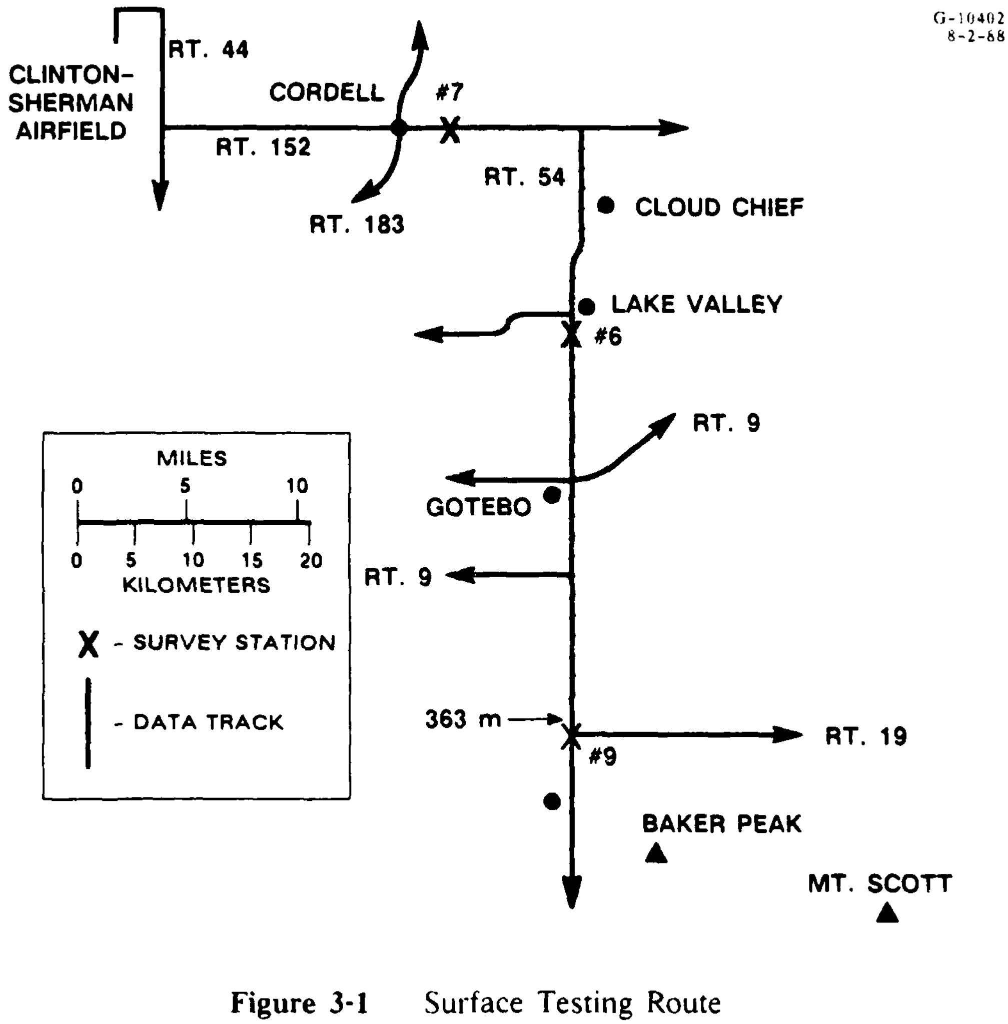


Figure 3-1 Surface Testing Route

of the instruments in the triad. Close examination of these data revealed no apparent anomalies; however, as with the airborne case, isolated spikes were present in the gravity gradients.

Three distinct techniques were applied to the surface data to measure the repeatability of the GGSS navigation outputs. The first involved examining expanded position profiles along constant-latitude and constant-longitude portions of the track. In the second technique, the tracks were synchronized in time and the minimum distance between them calculated. The third technique consisted of computing the total shift distance necessary to correlate corresponding segments of the elevation profiles from each track. A maximum difference of 20 m between tracks was observed after applying these techniques to the surface data. Since this bound on the position uncertainty exceeds the along-track resolution of the measured gradients (i.e., 40 m), the track-to-track repeatability is sufficient to assure adequate gradient registration accuracy (Ref. 11). As an independent check, available topographic maps were acquired to quantify the absolute position error of these two tracks. Close examination of the position data overlaid on the map revealed errors typically less than 10 m. The segment of track characterized by the right turn indicated in Fig. 3-1 is presented in Fig. 3-2.

The surface gravity gradients were resampled to provide new datasets with constant 40-m increments between adjacent samples (i.e., one sample approximately every three seconds at an average vehicle speed of about 12 m/sec). Track-to-track repeatability analysis was performed by 1) estimating spectral coherence and comparing results with separately estimated PSD models, and 2) estimating the along-track gravity disturbances using a Kalman smoother. Spectral coherence analysis was performed which yielded a 67% value of squared coherence for wavelengths longer than 10 km and 50% for wavelengths of 1.5 km. These values are consistent with the observed levels of signal and noise. The PSDs showed white noise floors of about 5300 and 5000 E^2/Hz for the 6 June and 9 June tracks, respectively. At this noise level the gravity gradients can be recovered by using a Kalman smoother; the theoretical rms error is less then 9 E. A summary of the repeatability of the gravity disturbance estimates is presented in Table 3-1. The repeatability results demonstrate good parameter stability despite the high noise level, and are consistent with the standard errors of the Kalman smoother. Note that the increased noise* observed in the surface (vs the airborne) data has the effect of reducing the required tiepoint spacing for a given level of gradiometer accuracy.

* Believed due to a mistuned suspension in the van which possesses a critical mode that heightens vibration response within the gradiometer passband near 0.5 Hz.

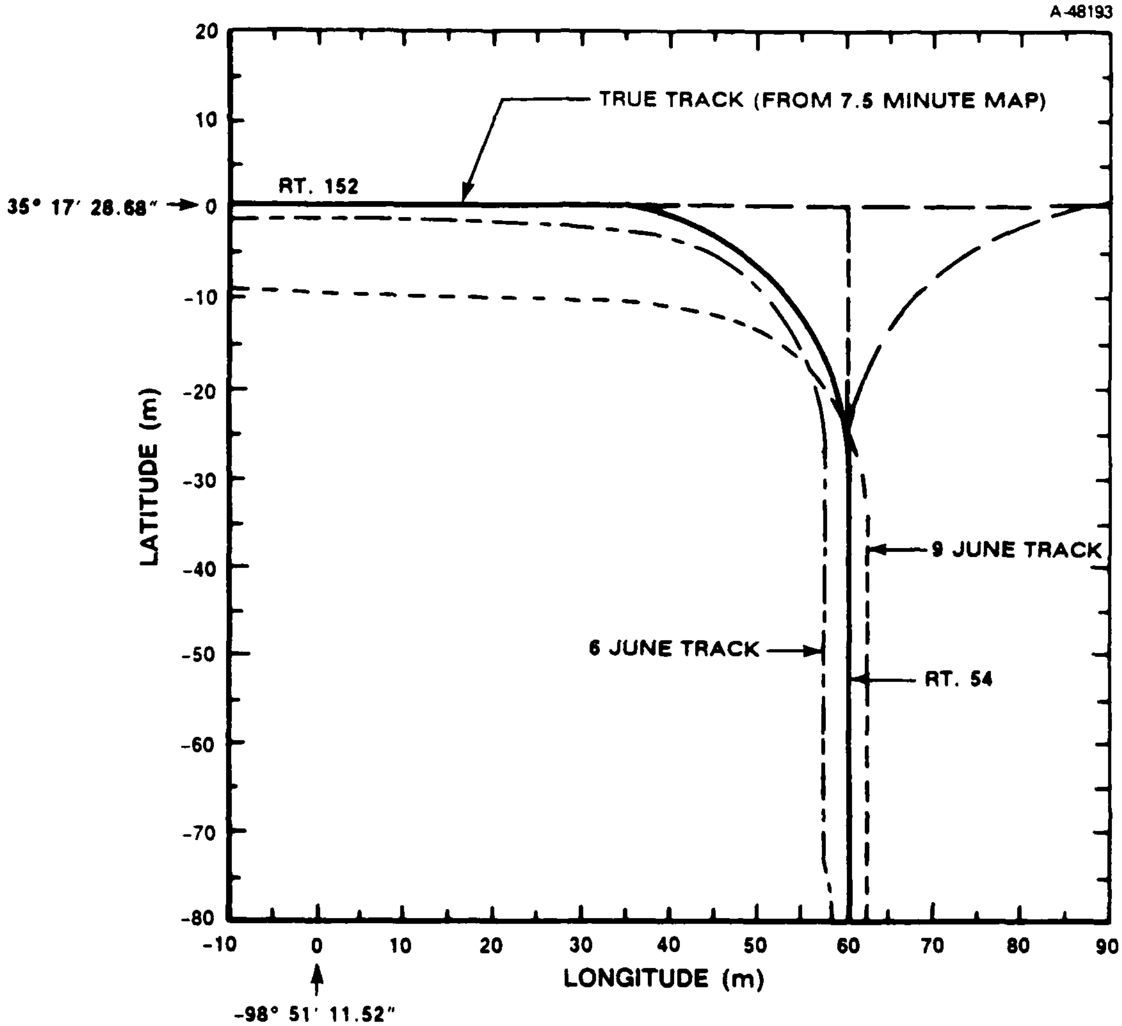


Figure 3-2 Comparison of Data Tracks with Topographic Map

Table 3-1 Summary of Repeatability of Gravity Disturbance Estimates

DISTURBANCE COMPONENT	TRACK-TO-TRACK COMPARISON	
	RMS DIFFERENCE	MAXIMUM DIFFERENCE
Along-track (mgal/arc sec)	2.1/0.44	4.3/0.90
Cross-track (mgal/arc sec)	3.2/0.67	5.8/1.2
Vertical (mgal)	2.5	5.0

Note: Tiepoint spacing for deflection quantities is 46.0 km; 52.8 km for vertical component.

4. SUMMARY, CONCLUSIONS, AND NEXT STEPS

The Gravity Gradiometer Survey System developed by Bell Aerospace has successfully gathered data in both airborne and surface survey scenarios. The GGSS navigation system has convincingly demonstrated high accuracy and reliability for both the GPS-aiding and fifth-wheel aiding mechanizations. Track-to-track repeatability of the gravity disturbance estimates from the surface application is encouraging, with rms results in the 2 to 3 mgal rms range for tiepoints about 50 km apart. Comparison of the airborne estimates with available truth data is also encouraging, with rms errors below 5 mgal based on single-track analysis with tiepoint spacing of about 90 km, and rms errors less than 2 mgal (tiepoints about 80 km apart) based on multi-track analysis. In all cases analyzed to date, actual rms errors have agreed well with predicted rms errors. *This demonstrates that significant error mechanisms in the GGSS have been modeled and accounted for properly.*

Although the GGSS program encountered the usual share of difficulties typical of test efforts, and was severely constrained by GPS limitations, the availability of the GGSS was quite remarkable. In fact, the only real problem with the tests was that so much data were lost. Of the 126 airborne data tracks that were flown, only 56 were of sufficient quality for Bell to even attempt Stage I data reduction. Of these 56, another 21 tracks were eliminated due to problems which were readily observed during TASC's quick-look review. If the usable data from the airborne tests is taken to be the 20 tracks presented in Table 2-1, the "data yield" figure of merit for the GGSS is only 16 percent.

Similarly, the surface tests generated only a small amount of useful data (two short tracks for almost two weeks of effort). The particularly unfortunate aspect of the low data yield is that, had timely near real-time review of each day's data been possible, much of the bad data could have been avoided. Problems could have been discerned and resolved prior to the collection of additional data. As attention turns toward preparing for the next phase of GGSS testing in Colorado and New Mexico, *it is crucial to provide a means to assure the quality of the data on a daily basis*. Note that in the more complex organizational environment of the Rail Garrison MX tests (vs the overall control enjoyed by DMA, AFGL, and Bell during the Oklahoma tests), GGSS data quality similar to that observed in Oklahoma will prove to be acceptable. However, the logistics of gathering the data will likely prove more difficult. In this

arena, if the data yield is not significantly improved, the system's credibility could be severely damaged. For this reason it is *recommended that a system be acquired and operated which assesses the GGSS test data immediately after each day of collection and grades that data for acceptability.*

In summary, the technical feasibility of the GGSS has clearly been demonstrated and operational surveys are possible today. Even with the overhead burden particular to the test program, it is evident that *the GGSS offers a significant increase in the ability to perform full gravity vector surveys in a timely and economical manner.*

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